MODEL DEVELOPMENT AND PERFORMANCE ANALYSIS OF INTEGRATED GASIFICATION PROCESS AND PROTON EXCHANGE MEMBRANE FUEL CELL

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

Faculty of Chemical & Natural Resources Engineering

UNIVERSITI MALAYSIA PAHANG

JANUARY 2019

ACKNOWLEDGEMENTS

First and foremost, I would like to thank to ALLAH for giving me a chance to complete this thesis. Actually, I definitely did not expect that out of all chapters in this thesis, writing down this acknowledgement section is going to be the hardest of all. However, I would try my very best and for individuals that are inadvertently omitted, I would like to propose my apologies and thank you for everything. As often said, old age comes in hand not only with wisdoms but also forgetfulness.

Secondly, I would like to extend my deepest gratitude to Abah, Muslim Ahmad and Umi, Zalina Zainon. Both of you have been the backbone of my entire being, my emotional support for the past 26 years. I do honestly hope I have made both of you proud. For my siblings, Umairah, Aini Khalida and Fatihah, well what I can say, all of you have been my support of strength, someone that I know I can look up to and always be there for me during my up and down.

Well, where would I be in my studies without my two esteemed supervisors and co-supervisor, Dr Noor Asma Fazli Abdul Samad and Dr. Suriyati Saleh, Thank you foremost for giving me the opportunity of lifetime to do my Master's here and most importantly for the never-ending trust, dedications, and faith not only in my ability but also in me personally. I also want to thank to all lecturers in Faculty of Chemical & Natural Resources Engineering (FKKSA) that always giving me advice and supporting me directly or indirectly. My deepest gratitude also goes to all technical and administrative staffs that had assisted me in thousand ways I could ever possibly imagine. I am also very much indebted to Ministry of High Education (MOHE), for providing me with the scholarship (MYBRAINS) throughout my duration of study here.

Next, to my best friends, Fakhrul Razil Alawi, Zakirah and Hazirah, thank you for being there always for me. You three certainly seen the inferior of me but yet never fail to bring out the best in me. To Ameerul Hakeem, Abu and Syafiq, thank you all for the times we spend together. We certainly define the meaning of working hard and playing harder, but ultimately; no matter how terrible the world goes at times, it will be better eventually when you have friends around to cheer you up. To my best mates, well I am truly proud and honored to share this ride along with all of you. Thank you so much. For everyone, cheers, and meet all of you again in the future.

MUHAMMAD BILAL BIN MUSLIM

21 JANUARY 2019

DEDICATION TO MY FAMILY

ABAH, UMI, MERAH, IDA & TEHAH

ABSTRAK

Ketika ini, jumlah permintaan tenaga dari seluruh dunia semakin meningkat selaras dengan pertumbuhan ekonomi. Kebanyakan sumber tenaga yang digunakan adalah berpunca daripada bahan api fosil yang merupakan sumber yang tidak boleh diperbaharui. Walaupun sumber bahan api fosil masih lagi banyak, permintaan tinggi terhadap sumber bahan api yang terhad ini tidak dapat dielakkan di mana sumber ini akan kehabisan kelak. Jadi, sumber tenaga yang boleh diperbaharui kini dilihat sebagai pilihan terbaik untuk menggantikan sumber bahan api fosil sebagai penjana utama tenaga. Sisa kelapa sawit merupakan salah satu alternatif untuk menggantikan bahan api fosil dimana sisa ini boleh digunapakai untuk penggunaan tenaga kerana jumlahnya yang banyak dan ketersediaannya di Malaysia. Sisa ini boleh digunakan untuk menghasilkan produk yang berguna seperti gas sintesis untuk penjanaan tenaga. Oleh itu, integrasi kerangka kerja bagi sistem penggegasan dan sel bahan api berasaskan membran pertukaran proton (PEMFC) telah dibuat untuk menghasilkan gas sintesis yang diperlukan dan penjanaan tenaga melalui langkah yang spesifik di dalam rangka kerja. Aplikasi rangka kerja ini diaplikasikan melalui lima kajian kes yang berbeza di mana setiap kes mempunyai objektif yang berlainan. Kesemua lima kajian kes meliputi pengesahan penggegas lapisan tetap dan penggegas lapisan terbendalir, perbandingan prestasi kedua-dua pengegas tersebut, penggegasan sisa kelapa sawit yang mentah dan telah ditorekfasi, kesan penulenan hidrogen serta penghasilan kuasa. Kedua-dua model penggegas jenis lapisan tetap dan lapisan terbendalir telah dibuat menggunakan perisian Aspen Plus dan keputusan pengesahan yang didapati adalah bertepatan dengan data kajian yang telah dijalankan. Jumlah hidrogen yang tinggi didapati dalam penggegas lapisan terbendalir berbanding lapisan tetap menunjukkan penggegas lapisan terbendalir memberi prestasi yang lebih tinggi dalam menghasilkan gas sintesis. Pelbagai jenis sisa kelapa sawit seperti pelepah kelapa sawit, tandan kelapa sawit, tempurung kelapa sawit dan gentian mesokarpa sawit telah digunakan sebagai bahan suapan untuk kedua-dua penggegas dan keputusan simulasi menunjukkan pelepah kelapa sawit menghasilkan 7.81 % dan 5.12 % gas hidrogen untuk penggegas lapisan terbendalir dan lapisan tetap. Untuk komposisi gas sintesis, pelepah kelapa sawit yang ditorefaksi pada 300 °C menghasilkan gas hidrogen tertinggi berbanding pelepah kelapa sawit yang mentah menunjukkan torefaksi merupakan cara rawatan yang dapat menambahbaik penghasilan gas sintesis. Kesan penulenan juga telah diuji dan menunjukkan lebih banyak gas hidrogen telah terhasil dan jumlah gas karbon monoksida telah dikurangkan sehingga di bawah paras 10 ppm bagi memenuhi prasyarat untuk menggunakan sel bahan api berasaskan membran pertukaran proton (PEMFC). Bagi penghasilan kuasa, pelepah kelapa sawit yang ditorefaksi pada 300 °C menghasilkan kuasa yang paling tinggi iaitu 5.74 kW dan 6.65 kW untuk penggegas lapisan tetap-PEMFC dan penggegas lapisan terbendalir-PEMFC. Dari segi kecekapan pula, untuk penggegas lapisan terbendalir-PEMFC, pelepah kelapa sawit yang ditorefaksi pada 300 °C menghasilkan 55.88 % untuk kecekapan elektrik, 74.24 % untuk kecekapan keseluruhan dan 34.98 % untuk kecekapan tindan sel bahan api. Manakala untuk penggegas lapisan tetap-PEMFC, pelepah kelapa sawit yang ditorefaksi pada 300 °C menghasilkan 48.27 % untuk kecekapan elektrik, 69.47 % untuk kecekapan keseluruhan dan 27.74 % untuk kecekapan tindan sel bahan api. Kesimpulannya, integrasi kerangka kerja untuk penggegasan dan PEMFC boleh digunakan sebagai alat untuk penjanaan tenaga dan penunjuk kecekapan manakala torefaksi sebagai cara rawatan boleh meningkatkan penghasilan gas hidrogen dan penjanaan tenaga.

ABSTRACT

The total energy demands from the entire global are increasing every day in order to support economic growth. Most of the sources of energy used are coming from fossil fuel which is non-renewable energy sources. Although there are still large supplies of fossil fuel, it is inevitable that one day the amount of fossil fuel will be decreased and running out. Hence, the renewable energy sources are currently identified as the best choice for replacing the fossil fuels as main energy supply. Palm oil wastes as the alternative for fossil fuel substitution have the potential to be utilized for energy purpose due to its abundances and availabilities in Malaysia. This biomass can be used to produce useful product such as synthesis gas which can be utilized for power production. Thus, an integrated workflow of biomass gasification and PEMFC has been developed for producing the required synthesis gas and power production. The applications of the integrated workflow are highlighted through five different case studies which each have different objectives. All five case studies are covering the model validation of fixed and fluidized bed gasifiers, performance of the gasifiers, gasification of raw and torrefied palm oil wastes, and effects of purification on the hydrogen and power production. Both models of fixed and fluidized bed gasifiers have been developed in Aspen Plus software and the validation results obtained are in good agreement with literature data. Higher amount of hydrogen gas was obtained in fluidized bed gasifier compare to fixed bed gasifier which indicates fluidized bed provides better performance for producing synthesis gas. Palm oil wastes such as Oil Palm Frond (OPF), Palm Kernel Shell (PKS), Palm Mesocarp Fiber (PMF) and Empty Fruit Bunch (EFB) have been used as inputs for both gasifiers and the simulation results show the OPF obtained 7.81 % and 5.12 % of hydrogen gas for fluidized bed and fixed bed gasifiers respectively. For synthesis gas composition, the torrefied OPF at 300 °C provides the highest hydrogen production compare to raw OPF indicating torrefaction as pre-treatment method is able to improve synthesis gas production. The effects of purification have been tested where more hydrogen gas are produced and the amount of carbon monoxide (CO) is reduced below 10 ppm which is the allowable amounts as input for Proton Exchange Membrane Fuel Cell (PEMFC). For power production, torrefied OPF at 300 °C provides the highest power produced around 5.74 kW and 6.65 kW for integrated fixed bed-PEMFC and fluidized bed-PEMFC respectively. In terms of efficiencies, for integrated fluidized bed-PEMFC, the torrefied OPF at 300 °C produces 55.88 % for electrical efficiency, 74.24 % for overall efficiency and 34.98 % for stack efficiency. Meanwhile for integrated fixed bed-PEMFC, the torrefied OPF at 300 °C produces 48.27 % for electrical efficiency, 69.47% for overall efficiency and 27.74 % for stack efficiency. In overall, the integrated gasification and PEMFC is able to be used as tools for power production and efficiency indicator and torrefaction as pre-treatment method is a useful for upgrading the hydrogen and power production.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

E_{cell}	Cell voltage
E_R	Reversible cell potential
η_a	Activation loss at the anode
η_c	Activation loss at the cathode
η_{ohmic}	Ohmic loss (V)
R	Ideal gas constant ($Jmol^{-1}K^{-1}$)
T	Operating temperature (K)
α	Charge transfer coefficient
F	Faraday constant (C/mol)
i	Quantity of current density (Acm^{-2})
keh	Rate constant of hydrogen electro-oxidation (Acm^{-2})
θ_h	Fractional surface coverage of hydrogen
i_{oc}	Cathode exchange current density (Acm^{-2})
n	Number of cells used in PEMFC
R_{ohmic}	Ohmic resistance
A	Area of the active cell (cm^2)
y_{ie}	Experimental values
y_{ip}	Predicted values
N	Number of data points
P_{actual}	Exact value of the data
$P_{measured}$	Approximate value of the data
V	Cell voltage (V)
$\dot{m}_{PG}$	Mass flow of product gas (kg/h)
$\dot{m}_{Bio}$	Mass flow of biomass (kg/h)
P_e	Amount of power produce from the PEMFC
P_h	Amount of thermal energy from the PEMFC
$\eta_{electrical}$	Electrical efficiency
$\eta_{therma}l$	Thermal efficiency
$\eta_{overall}$	Overall efficiency
η_{stack}	Stack efficiency
E	electric energy input
P_{fc}	Output power produced by PEMFC (W)

LIST OF ABBREVIATIONS

AMFCs	Alkaline Membrane Fuel Cells
ABR	Air to Biomass Ratio
AFC	Alkaline Fuel Cells
CGE	Cold Gas Efficiency
CO-PROX	Catalytic Preferential Oxidation of CO
DMFCs	Direct Methanol Fuel Cells
EFB	Empty Fruit Bunch
FC	Fixed Carbon
HHV	Higher Heating Value
HTS	High-Temperature Water Gas Shift Reactor
LHV	Lower Heating Value
LTS	Low-Temperature Water Gas Shift Reactor
MC	Moisture Content
MCFCs	Molten Carbonate Fuel Cells
OPF	Oil Palm Frond
PAFCs	Phosphoric Acid Fuel Cells
PEMFC	Proton Exchange Membrane Fuel Cell
PKS	Palm Kernel Shell
PMF	Palm Modecate Fibre
PR-BM	Peng Robinson with Boston-Mathias
PROXANAL	Proximate Analysis
RKS-BM	Redlich-Kwong-Soave with Boston-Mathias
RMSE	Root Mean Square Error
SBR	Steam to Biomass Ratio
SOFCs	Solid Oxide Fuel Cells
ULTANAL	Ultimate Analysis
VM	Volatile Matter

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